GROUND CONTROL IN OPEN PIT MINES

Discussion on Various Aspects and Practices

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Abstract

Slope failures and ground instability at surface mining operations contribute to nearly 15% of surface mining fatalities. Knowing how to properly design slopes with respect to geologic structures will help minimize slope failures. Carefully designed monitoring programs are very useful for supplementing safe operational practices. A properly designed monitoring program will also send warnings of impending instability and provide the necessary geotechnical information for designing appropriate corrective measures. Future technologies may overcome the limitations of current monitoring equipment, but until that time, diligent inspections of the highwalls above workers is crucial. Understanding and recognizing warning signs of impending ground instabilities will hopefully reduce the injury and fatality rates at surface mining operations.

The potentially hazardous nature of open pit mining requires the application of sound geotechnical engineering practice to mine design and general operating procedures, to allow safe and economic mining of any commodity within any rock mass.

This paper covers the identification of hazards and control of risks associated with stability of open pit mine slopes, and concerns the safety of both employees and machinery. It is to assist relevant mining personnel with the development of procedures relating to the application of sound ground control practice in open pit mines.

1. INTRODUCTION - Ground control is the methodology applied to maintain all the risks associated with various forms of ground instability in open pit mine slopes within an acceptable level. Ground refers to all natural geological materials in an open pit mine, which may range from weak clay or sand to hard rock.

Ground instability that may cause or have the potential to cause harm to personnel working in an open pit mine, such as:

- Slumping, sliding, toppling or falling of material involving a part or the whole of a pit slope,
- Ravelling or falling of pieces of rock or rock like material from a pit slope, and
- Any combination of the above failure modes.

Ground instability hazards can result in serious harm or death of mine workers or other persons that may enter a mining area. For example, the outcome of the hazard of a loose piece of rock falling from a pit wall and striking someone can be fatal by either direct physical contact, or damaging the plant or vehicle in which the person is working or travelling. A collapse or failure of part or whole of

a pit slope could cause injury or death due to the immediate contact with the collapsing material or due to the effects of physical entrapment within failure debris.

In an open pit mine, uncontrolled instability or movement of material in the pit slopes can have many ramifications including:

- Loss of life or injury to persons working or visiting the mine (Safety factors)
- Loss of worker income, loss of worker confidence, loss of corporate credibility, increased legal liability (Social factors)
- Disruption of operations, loss of ore, loss of equipment, increased stripping, cost of cleanup, loss of markets (Economic factors), and
- Collapse of nearby infrastructure/facilities into the open pit, for example, mine waste dumps, tailings storage facilities etc, and interference with natural drainage (Environmental factors).

As can be seen from the above list, in addition to the improved safety, sound ground control practices in open pit mines lead to social, economic and environmental benefits as well. Controlling the potential for hazardous ground movements or instability in an open pit mine slope to within acceptable limits is essential to eliminate or minimise the safety risks.

2. GROUND CONTROL IN OPEN PIT MINES - Open pit slopes are generally designed as a series of batters separated by berms, which are provided at predefined vertical height intervals of the slope (Figure 1). The principal functions of berms are to catch and retain any material falling from the batter faces and crest and to improve overall slope stability. Access to a pit is usually via a ramp that may spiral around the pit or be located on one side of the pit with switchbacks at each end. A succession of batters between two access ramp sections (or between a ramp section and the pit floor or pit crest) is defined as the inter-ramp slope. The inter-ramp slope angle is always flatter than the batter angle in that slope. The full height of a pit slope, from the toe to the crest, comprising several batters separated by berms (and access ramp sections if the ramp is on that slope) is the overall slope. Figure 1 illustrates the terminology used.

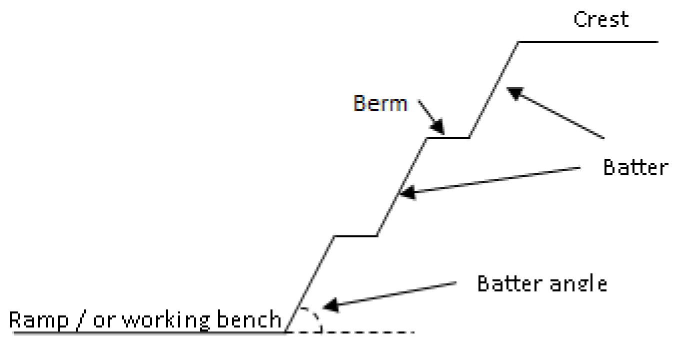
Ground control – to be effective in an open pit mine – requires the diligent application of geotechnical engineering practices to pit slope design, construction, maintenance and abandonment. Geotechnical engineering deals with the whole spectrum of natural geological materials ranging from low strength soils to high strength rocks, thus it can be divided into two sub-disciplines:

(a) Soil engineering, which deals with the engineering behaviour of soils, and

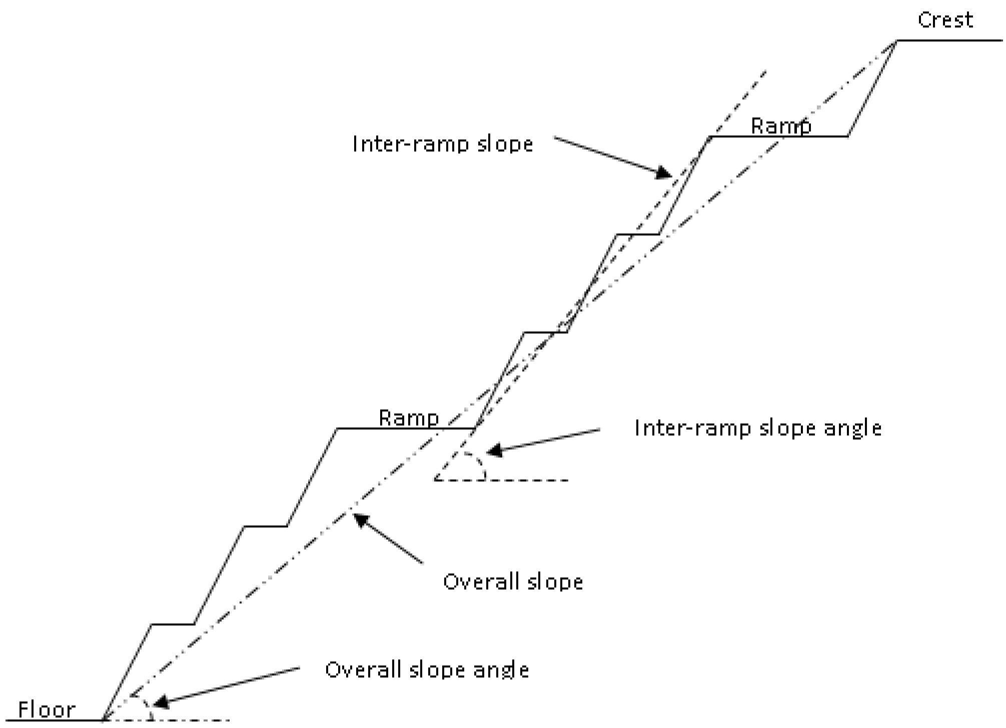
(b) Rock engineering, which deals with the engineering behaviour of rock.

An open pit mine may be excavated within relatively uniform material types or combination of materials. In many open pits, the wall profile may take the form of a completely weathered rock (with essentially soil like engineering properties near the surface), grading through highly to slightly

weathered rock (with both soil and rock engineering properties) to hard fresh rock materials at depth.



(a) Batter Details



(b) Inter-Ramp and overall slope details

Fig - 1 (Pit slope terminology)

Subsequently, pit wall design is a significantly challenging task, and the mine operator must ensure that, through the diligent application of sound geotechnical engineering practice, safe open pit mine slopes are maintained in any geological environment. Examples of factors to be considered with respect to maintaining effective ground control / safe working conditions include:

- Strength of materials within the slope

- Geological structure
- Surface water (including extreme rainfall events) and groundwater
- Slope geometry excavation quality control
- Rock damage from mass blasts, poor blasting or excavation practices
- Scaling and cleanup of excavated pit slopes and berms
- Surcharge loading from mine infrastructure (i.e. waste dumps, tailings storage facilities and haul roads etc)
- The presence of nearby underground mine voids
- Vibration due to blasting and seismic events
- In situ or mining induced stresses, and
- Time dependent deterioration of rock/soil materials.

This list illustrates that effective ground control (EGC) is achieved by the successful management of four basic disciplines in an open pit mine: geology, planning, geotechnical and production (Figure 2). In general, the four disciplines may operate independent of each other. However, as illustrated by Figure 2, the mine operator needs to be aware each can have an effect on the other, and therefore must develop an integrated approach to maintain EGC at all stages of mining.

It is also essential that all personnel involved with each discipline are adequately trained in their role and that they interact to the level required to ensure EGC is maintained at all stages of mining.

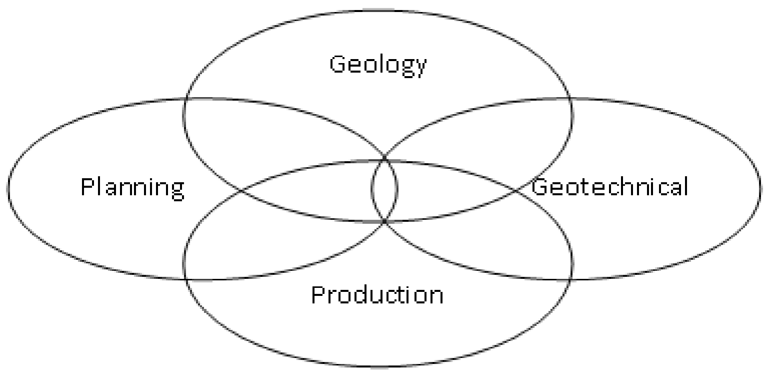


Figure 2

Further discussion with respect to each of these disciplines and their effect on EGC is provided in the following sections.

I) Mine Planning - The importance of a systematic approach to managing mine planning issues with respect to attaining EGC cannot be over-emphasised. Open pit mines represent a complex

engineering system with many sub-systems that need to function in an integrated manner for the mine to operate safely and economically.

Financial constraints, for instance, prohibit the mine from being designed for “permanent” stability, such as in civil engineering projects. Legal constraints can require significant alterations to mine designs; some of these may impact significantly on the economic viability of the mine.

The mine planning and design (MPD) process has several phases - usually involving a conceptual study, a preliminary or pre-feasibility study, a feasibility study, and culminating at detailed design for commencement and closure of the project.

The words “mine planning” and “mine design” are sometimes used interchangeably; however, they are more correctly seen as separate but complementary aspects of the engineering method. Mine planning deals with the selection and coordinated operation of sub-systems such as mine production capacity, workforce numbers, equipment selection, budgeting, scheduling and rehabilitation. Mine design deals with sub-systems such as excavation geometry, production and development blasting, power, water control (for example, pumping and depressurisation), gas and dust control, and ground support and reinforcement.

A formal MPD process is to be established early in the life of a mine; using the “mine commencement design” as the basis. Such a system might involve regular formal meetings, as often as required, dealing of a range of planning and design issues in the current operational areas and the new areas of the mine.

It is acknowledged that feasibility and commencement mine designs will be modified with time, as additional data becomes available during operation; however, it is essential that the commencement design be adequately attuned to the anticipated local ground conditions* before mining commences. In this way, the potential for hazardous ground movements to occur unexpectedly when mining commences is minimised significantly.

As the mine matures, the MPD process is expected to be closely attuned to site ground conditions and any mine site or corporate restraints.

The “MPD process meetings” should be interdisciplinary requiring the involvement, as necessary, of a range of expertise including: survey, geology, mining engineering, drilling and blasting, geotechnical engineering, rehabilitation, workforce supervision and management (principal and contractor).

It has been found that notes from earlier mine planning meetings can form a valuable summary as to why certain mining decisions have been made and thereby assist with decision making in the present and future. This is considered to be a great asset for mines with a high turnover of staff.

It is also necessary, as part of the MPD process, to adopt a formal mining approval process for the development and/or mining of currently producing or undeveloped mining blocks. This formal mining approval process should include the production of plans, cross-sections and longitudinal projections of the mining block(s), as appropriate, plus a written description of the proposed mining work to be done and the mining issues that need to be addressed. A draft mining plan and the

associated notes for the ore block(s) in question should be issued, in a timely manner, for discussion at subsequent MPD process meetings. Following discussion and resolution of the issues, final approved mining plan(s) and notes can be issued.

The formal mine plan approval process is to include the signatures of the people responsible for each relevant component of the plan - for example, survey, geology, drilling and blasting, loading and haulage, geotechnical, planning and design aspects plus the Quarry Manager and the Registered Manager - as appropriate.

Similar to the other inputs required for the MPD process, the form and extent of geotechnical inputs changes during the life of the mine (LOM). The use of geotechnical information and the accuracy required at each stage can vary considerably depending on the characteristics of a given deposit and the perceived risks.

In general, geotechnical inputs to the MPD process start with high level of assumptions when projects are at early-stage analysis. Furthermore, during the early stages of mine design there is usually limited detail available of the overall ground conditions of the pit slopes, and it is necessary to make a number of simplifying assumptions to arrive at a geotechnical slope design. During the latter stages, more complex and detailed inputs are required for pit wall and operations planning and design. It follows that, in latter stages, when mining is at its deepest and most restricted at the pit floor, the mine operator must have a suitably high level of understanding of the geotechnical parameters relevant to maintain safe operating conditions in the pit.

II) Geotechnical Design of Pit Slopes - The geotechnical design process for open pit slopes, regardless of the size of the pit or materials mined, shall adopt the following strategic approach:

a. Site investigation.

b. Formulation of a geotechnical model for the pit area.

c. Division of the model into geotechnical domains and design sectors.

d. Slope design and stability assessment for the geotechnical domains/design sectors.

e. Design implementation and definition of monitoring requirements.

a. Site investigation - Site investigation is the process by which geotechnical and all other relevant information which might affect the design, construction and performance of the open pit mine slopes is acquired. The information collected during a site investigation program include data on the mining history, topography, geomorphology, climate, drainage, physical geology, geologic structure, tectonic evolution, lithology, rock mass properties and hydrogeology etc relevant to the project and the perceived risk. Collection of this information for the geotechnical design of pit slopes should begin from day one in the development of a project. Several tools and techniques are available to the mine operator for data collection for geotechnical design of open pit slopes. These include geophysical methods, outcrop mapping, core drilling and logging, field and laboratory testing for intact rock material and rock mass properties, geotechnical mapping of any existing pit slopes and underground excavations and mapping of current pit slopes once mining has commenced.

At early stages of a project, surface geophysical methods such as seismic refraction, resistivity and electromagnetic surveys can be used to develop a 3D image of zones proposed for mining. These techniques permit the preliminary demarcation of major lithological units and major structural features such as fracture zones. The information gathered from such techniques is then used in the planning of drilling programs for obtaining detailed information required for the design process.

Prior to the commencement of mining, much needed subsurface information for pit slope design, within acceptable levels of confidence, can be obtained by core drilling and logging. By advance planning and scoping, the core drilling programs primarily aimed at mineral exploration and resources evaluation purposes can be used to extract geotechnical information. Notwithstanding the above, core drilling programs primarily executed for geotechnical data collection will also be required to gain an adequate understanding of the subsurface conditions before a geotechnical design can be produced for the commencement of mining. Obviously, the number of geotechnical holes required for a particular project will depend on the level and reliability of already available geological and geotechnical information of the site, the complexity of site geology and the size and operating life of the project. Core samples recovered from boreholes can be logged by traditional methods of direct observation or using digital photography. Suitable software is now available for the analysis of data recorded by the latter mentioned method. Boreholes can also be logged using downhole cameras and downhole geophysical techniques.

Data collection from exposed rock surfaces, particularly the data on orientation, spacing, length and surface waviness of geological structures, can also be carried out using 3D digital photogrammetric techniques. With these techniques the data can be gathered remotely and accurately from areas where access is difficult or unsafe. Such techniques permit accurate low-cost mapping of pit slopes at a rapid rate. The data collected by these techniques can be downloaded into mine planning software and used in real time for mine planning, design and operating purposes.

The geotechnical data collection by means of outcrop mapping, drill core logging and pit slope mapping etc should be carried out by experienced professionals such as geologists, engineering geologists and geotechnical engineers, or properly trained geotechnicians under the supervision of either engineering geologists or geotechnical engineers.

b. Formulation of a geotechnical model - The availability of a comprehensive geotechnical model is the fundamental basis for all slope designs and is comprised four component models:

- Geological model,
- Structural model,
- Rock mass model,
- Hydrogeological model.

Several computer-based modelling tools are available for the development of 3D geotechnical models. These tools permit visualisation and construction of comprehensive models that can include

geological and structural information, ore grade distributions, groundwater distributions, and a variety of geotechnical details. Constructing these models is a useful exercise because it facilitates visualisation of the interrelationships between the various types of information displayed by the model, and recognition of the deficiencies in the database. Additional information that may be included in the geotechnical model includes climate, surface drainage and regional seismicity. During model construction process deficiencies and anomalies in the data become obvious and these provide useful guidance for further site investigation programs. As new information becomes available the model should be updated and the design should be modified or fine-tuned as required.

The geotechnical model comprising the four components must be in place before the subsequent steps of setting up the geotechnical domains, allocating design sectors and preparing the final slope designs can commence.

Geological model - The purpose of the geological model is to permit a three dimensional visualisation of the material types that will be present in the pit slopes. Different material types often have different strength characteristics, which require due attention and consideration in the process of pit slope design. The model should describe the regional and mine site geology and provide clear and unambiguous information on location and extent of different material types, i.e. lithology, the degree and type of alteration or weathering, which can significantly change material properties. The model may be constructed in two or more layers depending on the site conditions. For instance rock units and their boundaries may be presented in one layer and the degree of weathering or alteration of rock units may be presented in the next. If the entire rock mass is overlain by a thick deposit of soils a third layer may be included in the model. The geological model is the starting point of geotechnical model and is essential to the slope design process of any open pit mine.

The development of an accurate, well-understood geological model is a task that should be undertaken by engineering geologists or geotechnical engineers with substantial contribution and inputs from exploration and mine geologists of the project. It requires an understanding of geological events that led to the formation of the ore body, regional and local structure, lithology, topography, morphology, regional stress field, as well as geotechnical requirements for pit slope design. The model should represent a broader view of the geology of the deposit, including the surrounding waste rock, focussing on the engineering aspects. This differs somewhat from that required by mine geologists, whose focus is primarily on mineralisation.

Structural model- The purpose of the structural model is to describe the orientation and spatial distribution of the structural defects (discontinuities) that are likely to influence the stability of pit slopes. The defects include faults, folds, foliation and bedding planes, joints, cleavage etc, and can be divided into two groups:

a) large structural features such as folds and faults that are widely spaced and continuous along strike and dip across the entire mine site (major structures), and

b) closely spaced joints, cleavage and faults etc that typically do not extend for more than two or three mining benches or batters (minor structures).

The presence of major structural features such as through-going faults that are relatively widely spaced can be detrimental to the stability of inter-ramp and overall slopes. While their effect on the stability of pit slopes must be fully assessed and the design must take that into consideration, they can also be used to subdivide the mine into a select number of structural domains, within which more closely spaced fault and joint fabric could control stability, particularly at batter and inter-ramp scales. Each of these domains will have distinct boundaries defined either by major structures as already mentioned or by lithological boundaries. They will be characterised internally by a recognisable structural fabric that clearly differentiates it from its neighbour.

The structural model should be developed using computer based 3D modelling tools. Ideally, in the structural model the major and minor structures should be recorded in at least two separate overlays. This allows efficient assessment their combined effect as well as separate effect on the stability of the pit slopes.

The task of developing the structural model is one for an experienced structural geologist. Exploration and mine geologists are an essential part of the modelling team, but the team leader should be a structural geologist who has the specific skills and the experience in structural geology.

Rock mass model - This model represents the engineering properties of the rock mass, which comprises various material types and structural defects, in which the open pit slope will be excavated. The rock mass properties include the properties of the intact pieces of rock, the structures that cut through the rock and the rock mass itself. These properties govern the performance of the slope and therefore the design approach.

In a slope constructed in stronger rocks failure could occur along geological structures which are considered as pre-existing planes of weakness in an otherwise solid rock. In relatively weak materials (i.e. weathered or soft rock) failure can propagate through the intact material, and/or along geologic structures. In some situations, in strong rocks as well as in weak materials, failure could propagate partly along geological structures and partly through intact rock material. It follows, therefore, that failure of an open pit slope could be governed by the strength of intact material or the strength of geological structures or both. It is therefore important to determine the engineering properties of (1) intact rock/soil, (2) structural features and (3) the rock mass in the various geological units present in a pit slope.

The information that must be included in the rock mass model may vary depending on the size and depth of the open pit mine, the complexity of the geological, structural, geotechnical and hydrogeological conditions of the site. In general the information that should be included in the model is:

- Intact rock material properties: unit weight, porosity, compressive strength, tensile strength, friction angle, cohesion, and elastic constants.
- Properties of structural defects: defect surface roughness, waviness, infilling materials, aperture size, wall strength, spacing and persistence as well as shear strength (friction angle and cohesion), and normal and shear stiffness, if numerical modelling of slope stability is envisaged.

- Rock mass properties: shear strength and deformation modulus.

The slope or mine scale shear strength and stiffness of structural defects are functions of defect wall strength, surface roughness, waviness, infilling materials and the aperture size. These properties must be taken into consideration to obtain reliable shear strength and stiffness values for geological defects in a pit slope.

Shear strength of structural defects can be determined in a laboratory or in situ using direct shear test apparatus. Relatively inexpensive laboratory testing can be conducted on defect samples collected from core drilling or saw cut discontinuities. In situ tests, on the other hand, are expensive and are difficult to conduct due to the problems associated with the preparation of test sample and application and maintenance of required loads during the test. Both laboratory and field tests have the problem of scale effects as the surface area tested is usually very much smaller than the one that could affect the stability of a pit slope. Nevertheless, the laboratory tests are useful to determine the basic friction angle (ϕ_b) of saw cut defects which is approximately equal to the residual friction angle of natural defects. More reliable values of defect shear strength parameters can be obtained from back-analysis of structurally controlled failure in existing pit slopes. However, this requires very careful interpretation of the failure mechanism, conditions that trigger the failure, and judgement to assess most probable values for the shear strength parameters.

For the analysis of failure through the rock mass it is necessary to determine the friction angle and cohesion of the rock mass itself. However, testing of representative rock mass samples is difficult because of sample disturbance and equipment size limitations. Thus the preferred method has been to derive empirical values of friction and cohesion based on rock mass rating systems that have been calibrated from experience. These ratings systems have been mainly developed for civil engineering tunnelling and underground mining applications. Some of them were subsequently extended for the use in rock slope engineering, and those that are commonly used include Tunnelling Quality Index (Q) (Barton et al., 1974), Rock Mass Rating (RMR) (Bieniawski, 1973, 1976, 1979, 1989); Mining Rock Mass Rating (MRMR) (Laubscher, 1977, 1990; Jakubec & Laubscher, 2000; Laubscher & Jakubec, 2001); and Geological Strength Index (GSI) (Hoek et al. 1995, 2002).

Hydrogeological model - The presence of groundwater in a pit slope may have significant negative effects on its stability. In the case of open pit mines excavated within weak materials such as clay or completely weathered rock, pore pressures play a significant role on the stability of pit slopes. High pore pressures reduce the effective stresses with a concomitant reduction in the shear strength of both soil/rock material and rock mass. This could lead to instability in the pit slope. High water pressures also reduce the shear strength of structural defects in an unweathered strong rock, leading to structurally controlled instability. Groundwater, depending on chemistry, can contribute to corrosion of ground support and reinforcement, if used as a method of slope stabilisation. This would significantly reduce their effectiveness.

Groundwater can also create saturated conditions and lead to water ponding within the pit which in turn may lead to unsafe working conditions. Other problems that could result from saturated conditions or standing water in the pit include loss of access to all or part of the pit, difficulties in the use of explosives for rock blasting, and reduced efficiency in the mining equipment used in the pit. It

is therefore important to develop a good groundwater model at early stages of any open pit mining project, so that effective control measures can be designed and implemented to minimise the adverse effects of the groundwater regime. This again is a task that should be undertaken by an expert with qualifications and experience in hydrogeology and its effect on open pit mining.

In open pit mines excavated below the groundwater table, dewatering or depressurisation may be necessary for the above mentioned reasons. This however depends on several factors, including:

- Hydrogeological characteristics of the rock mass.
- The depth of the excavation below the water table.
- The effect of groundwater on the materials and structures present in the pit slope.

The hydrogeological environment of an open pit should be well understood to ensure that adequate provision is made for the removal of groundwater from the pit. By means of a suitable program of investigation the hydrogeological characteristics of the rock mass within which the open pit mine is to be developed should be established before the commencement of mining. Preliminary data required for the development of hydrogeological model can be obtained from boreholes drilled for resources evaluation and geotechnical site investigation. Nevertheless, purpose designed drilling and testing programs will be required for the hydrogeological characterisation of the rock mass.

The obvious benefits of dewatering and depressurisation are improved performance of pit slopes, increased efficiency of blasting operations and mining equipment.

c. (i) ***Building the geotechnical model-*** The data compiled in the four components discussed above is to be used to construct the geotechnical model of the open pit mine. This is a step by step process of bringing successive layers of individual or combinations of individual data sets into a 3D solid model using computer based modelling tools. This, however, is an evolving process through various stages of a project. Where deficiencies exist, additional data must be gathered and the model updated.

The geological model, depicting the rock type boundaries within the mine, is the starting point and represents the first layer of the geotechnical model. The layers of other information such as rock mass weathering, structural data, rock mass properties as well as hydrogeological data can now be added step by step. As mentioned previously, the availability of a comprehensive geotechnical model is the fundamental basis for all slope designs.

(ii) ***Geotechnical domains and design sectors-*** Before the slope design and stability analysis can commence the pit is to be divided into geotechnical domains, each with its own geotechnical characteristics which are different from those of its neighbours. These characteristics will govern the stability depending on the orientation of pit slopes. The number of geotechnical domains relevant to pit wall design can vary significantly. For instance, the geotechnical domains may entirely be based on the structural model if other model parameters do not have a significant impact on ground control.

Conversely, large pits, excavated in a complex geotechnical environment may have several domains. Identification of geotechnical domains within the geotechnical model requires experience and judgement, and is a task that should be undertaken by geotechnical experts.

The geotechnical design of pit slopes is to be based an evaluation of the possible modes of failure including those controlled by geological structures. Where structure is expected to be the controlling factor as in the case of stronger rocks, the slope orientation may exert an influence on the design criteria. For instance, the structures in a particular geotechnical domain when combined with a particular slope orientation may have a greater potential for structurally controlled instability. For a different slope orientation in the same geotechnical domain, the potential for structurally controlled instability may not be the same. Therefore a further subdivision of a domain into design sectors may be required, based on the slope orientation and kinematically possible failure modes. The design sectors can also be defined based on operational considerations. For instance, a slope with a haul ramp requires different stability criteria than a slope without a ramp in the same geotechnical domain. The subdivision of domains into design sectors can reflect control at all levels, from batter scale, where minor structures (or fabric) provide the main control for batter angles, up to the overall slope scale, where a particular major structure may influence a range of slope orientations within a domain.

*d. **Geotechnical slope design and stability analysis-*** In open pit mining, there is a general tendency to increase the slope angle with the intention of decreasing the waste rock stripping which in turn may generate higher return on investment. However, increasing the slope angle decreases the stability of the slope, which could lead to safety implications and higher operating costs due to slope failures. Thus for any open pit mine to be successful the slopes must be constructed to an optimum angle (at batter, inter-ramp and overall scales) without compromising both safety and economics. The geotechnical slope design is the process of determining the optimum slope angles and dimensions for open pit mines. This process involves identification and analysis of all potential failure modes that could affect batter, inter-ramp and overall scale slopes, and begins with the division of the geotechnical model into geotechnical domains with similar geological, structural and rock mass characteristics. These characteristics should be used as the basis of assessment of possible failure modes in each domain or in each design sector, if the domains have been subdivided into design sectors.

In any open pit mine slope constructed in soils and weaker rocks the strength of slope materials can be the factor controlling the potential failure modes. For example, in cohesive soils, and in some weak or soft rocks, failure may occur as rotational shearing though slope material. However, there could be exceptions in weak or soft rocks in which relict joints or other incipient structures may be the primary control.

In stronger rocks, structure is likely to control stability. The typical structurally controlled modes of instability include plane sliding, wedge sliding and toppling, and are common in stronger rocks, especially at batter scale. Large scale structurally controlled failures are also possible in inter-ramp and overall slopes, if adversely oriented through-going structures are present. In general, structurally controlled sliding occurs when adversely oriented structural defects undercut or daylight in the slope. However, this is not always the case. In some rock masses with medium to low

strength, rock wedges and slabs that do not daylight could become unstable due to crushing and/or shearing through the rock mass/material at the toe. Moreover, depending on the number of defect sets present and their orientation the structurally controlled failure modes could have several variations to those mentioned above. The variations include step-path, step-wedge, active-passive blocks etc. In each case instability may be further aggravated when high water pressures are present in the pit slope. These must all be recognised by diligent analysis of the defect orientation data in each geotechnical domain.

When the orientation of defects is such that the formation of rock slabs, wedges or any other modes mentioned above is not possible, instability could still occur due to the movement on defects and failure through the intact rock material. Such failures, known as rock mass failures, may be assumed to occur by rotational shearing, similar to the failures in soil slopes. The possibility of rock mass failure particularly in overall and inter-ramp scale must also be fully assessed as part of the design process.

e. ***Design acceptance -*** A slope is considered to be stable when the forces resisting the potentially shearing, sliding or toppling mass of material on the slope are greater than the forces driving the mass. The resisting forces are provided by the strength of the rock material and/or geological structures, dependent on the mode of potential failure. Whereas the driving forces are primarily dependent on the unit weight of the rock, groundwater pressures in the rock mass, and any other forces exerted by in situ stress field or external loads such as loaded trucks on ramps, mine infrastructure near pit crest and seismicity etc.

The ratio of the resisting forces to the driving forces is termed the Factor of Safety (FOS) and has been the basis of stability acceptance criterion for many engineering applications. When the FOS = 1 the slope is considered to be in a state of “limiting equilibrium” and if the FOS > 1 the slope is considered to be theoretically stable. There are no strict criteria that specify the acceptable FOS, but for static loading conditions the values of 1.2 to 2.0 are commonly used depending on the type of slope and its importance. The FOS however is based on single values selected to represent the rock mass parameters used in the stability calculations. The reliability of the computed FOS depends on the selection of the single values from populations with significant distributions. In other words FOS is a random variable dependent on the distribution of the measured or estimated values of rock mass properties; for which the mine operator must take into consideration when developing slope design criteria.

An alternative approach to stability analysis is to use Probability of Failure (POF), whereby the probability of whether or not a slope will be stable is calculated from the distribution of input values. There are two options:

1. Recognising the FOS as a random variable and seeking the probability of it being equal to or less than 1. POF = P[FOS ≤ 1]
2. Seeking the probability that the driving force (D) exceeds the resisting force (R). POF = P[R – D ≤ 0]

In both options POF is computed using populations of rock mass parameters with significant statistical distributions.

As with FOS, there are no strict criteria that specify the acceptable POF. The literature shows that different guidelines are proposed by different authors. The acceptable values of FOS and POF proposed by Priest and Brown (1983) are presented in Table 1.

In open pit mines it is not uncommon to expect some degree of slope instability during mining. The acceptability of any failure depends on its consequences. From the point of view of the management of the mine there are unacceptable consequences including damage to equipment and infrastructure, economic impacts on production and costs of industrial and legal actions. If the failure of a particular slope is deemed to have no impact on the safety and production, then there is likely to be a minimal concern. For each open pit mine, it is therefore important to define the design acceptance criteria on a case by case basis based on the tolerable level of safety risk associated with slope failure in each geotechnical domain or slope design sector.

Table 1 : FOS and POF guidelines (after Priest and Brown, 1983)

		Acceptable values		
Consequence of failure	**Examples**	**Mean FOS**	**Minimum P[FOS<1.0]**	**Maximum P[FOS<1.5}**
Not serious	Individual benches; small (<50 m), temporary slopes, not adjacent to haulage roads	1.3	10%	20%
Moderately serious	Any slope of a permanent or semi-permanent nature	1.6	1%	10%
Very serious	Medium sized (50-100 m) and high slopes (<150 m) carrying major haulage roads or underlying permanent mine installation	2.0	0.3%	5%

f. ***Stability analysis-*** In geotechnical design of pit slopes the type of stability analysis is largely governed by the anticipated failure modes, the scale of the slope, the available data and the perceived risk relevant to the particular stage of the slope / mining project. Numerous slope stability packages exist; the mine operator is required to determine and verify the most applicable package suited to the conditions at their mines. The main types of slope stability analysis that should be considered include:

- Kinematic analysis of structurally controlled failures: this is the analysis of removability of rock blocks from the slope without referring to the forces that cause them to move, and is based on stereographic projections (Hoek and Bray, 1981; Goodman, 1989; Priest, 1985, 1993; and Wyllie and Mah, 2004) and Block Theory (Goodman and Shi, 1985; and Goodman,

1989). This analysis is mainly applied for batter designs, but may also be used for large scale slope design, if anticipated failure is controlled by structures.

- Limit equilibrium analysis: this two dimensional method of analysis is widely used for the computation of FOS against rotational shear failure in soil slopes. The analysis can be applied to assess the FOS of structurally controlled "kinematically unstable" rock block and wedges in batter and inter-ramp scale. It can also be used to assess the FOS against failure through rock material or rock mass in batter, inter-ramp and overall slopes. The major limitations of the limit equilibrium analysis are that it assumes the unstable mass can be represented by solid blocks and it cannot represent deformation and/or displacement of the failing rock mass.

- Numerical analysis: this is based on numerical modelling tools such as finite element and distinct element methods. It can overcome some of the limitations in the limit equilibrium analysis in that it can model complex rock masses and the deformation and displacement of the failing mass. This analysis is useful for the assessment of inter-ramp and overall slopes in large open pit mines.

At early stages of a project, when the data are limited and the geotechnical model has not been fully developed, empirical approaches based on rock mass classification methods such as RMR (Bieniawski, 1973, 1976, 1979, 1989), MRMR (Laubscher, 1977, 1990; Jakubec & Laubscher, 2000; Laubscher & Jakubec, 2001) can be used for preliminary slopes design (for example, Haines and Terbrugge, 1991; Orr, 1992). These methods have limitations in that they do not specifically deal with any of the structurally controlled failure modes mentioned earlier. These methods are largely based on qualitative studies of rock mass failures. They are considered only useful for preliminary assessment of failure through the rock mass.

Furthermore, when developing stability analysis criteria, the mine operator must take into account the fact that engineering design procedures are based on various simplifying assumptions that may restrict the application of a particular design procedure in certain circumstances. There needs to be a clear understanding of the origins and the limitations of the various design procedures when applying them in geotechnical engineering.

i) ***Batter and berm design-*** As mentioned previously, open pit slopes are generally designed as a series of batters separated by berms, which are provided at predefined vertical height intervals of the slope. The principal function of the berms is to provide a safe environment for personnel and equipment that must work near the slope face.

In most open pit mines, batter heights are typically range from 10 to 20 m. In large open pit mines batter heights up to 30 m are not uncommon providing that the rock mass is strong and massive. From a safety point of view the final decision on the maximum batter height should be based on:

a) the reliability of the batter slope, i.e. stability under the potential failure modes, and

b) the availability of equipment for adequate scaling to remove loose pieces of rock that may fall creating potential safety hazards for personnel working near the slope.

For reliability of the batter design all possible failure modes should be identified and their stability is assessed by kinematic and limit equilibrium analyses as appropriate.

The berms must be wide enough to arrest potentially hazardous rockfalls and contain any spillage from the batters above. They should also allow long-term access to instrumentation for slope movement monitoring and groundwater monitoring. The decision on the berm width should also take into account the likelihood of achieving the design width. This depends on the geological structure as well as the level of blasting and excavation control.

ii) ***Inter-ramp slope design-*** A combination of batters between two access ramp sections in the pit is usually considered as the inter-ramp slope. There are no criteria governing the height of the inter-ramp slopes, except for its reliability in terms of stability against the potential failure modes.

The methods of analysis required for inter-ramp slope design are the same as those used for the batter design except for the fact that the scale is different. Inter-ramp slopes may fail by plane and wedge sliding and toppling in stronger rocks and rotational shearing in soils and weak rocks. For these failure modes kinematic and limit equilibrium methods of analysis can be used with due consideration of the large scale structures which might undercut the inter-ramp slope.

Additionally, there is the possibility of more complex failure modes involving failure through the rock mass, which require analysis by numerical methods. When designing inter-ramp slopes the batter stability immediately below and above the pit access ramp must also be considered. Batter instability immediately below could undermine the ramp whereas instability immediately above could spill onto the ramp resulting in safety hazards and restricted access.

iii) ***Overall slope design-*** The full height of a pit slope, from toe to crest, comprising several batters separated by berms and access ramp sections is the overall slope. Although the term “overall slope” is well defined and understood, it represents vastly different slope heights depending on the maximum depth of the open pit mine. Put simply, the overall slopes of 100 m and 1000 m deep pits will be 100 m and 1000 m, respectively. Thus, the methods of stability analysis that must be considered may vary depending on the height of the slope.

The stability assessment of overall slopes should include both structurally controlled failure and rock mass failure modes. In the case of the former usually the adversely oriented large scale through-going structures are considered. An exception to this would be the complex failure modes such as step-path failure involving the entire slope. In large open pit slopes, simple sliding of rock slabs or wedges leading to overall slope failure may not be possible. In such situations instability could occur due to failure through the rock mass. Such failure may occur by rotational shearing or along a “general failure surface” (in which part of the failure is structurally controlled and part is through the rock) can be analysed by limit equilibrium methods of analysis. However, in large slopes, due to the complexities in the rock mass and the failure mechanisms the slope behaviour can be better understood by analyses carried out using numerical methods. Several numerical tools are available for pit slope stability analysis. They are usually based on continuum and discontinuum models, and hybrid models are also available.

As mentioned earlier, at an early stage of a project when the available geotechnical data are limited, empirical methods may be used to assess the stability against rock mass failure. However, these methods have limitations and should not be used as the sole method of rock mass failure assessment of open pit slopes.

3. IMPLEMENTATION OF THE SLOPE DESIGN - In any open pit mining operation, prior to the commencement of mining, the design will usually be changed or modified with time, as detailed information is gathered by site investigation programs. After the commencement of mining the design may continued to be modified based on additional data which may not be available until the rock mass is exposed by mining. The additional data include both new information on the ore body and geotechnical information on the pit slopes. However, it is essential that the geotechnical design is incorporated into the mine plan before commencing the construction of final pit slopes so that the design can be fully implemented to achieve the desired outcome. This requires effective interaction of the three groups: planning, geotechnical and production as illustrated in Figure 2.

The implementation of the design typically involve minimising unnecessary damage to slopes during blasting, excavation control and scaling, groundwater and surface water control, and installation of ground support and reinforcement, if included in the design. From the point of view of the production group, these measures are an addition to the production cost however they are required to improve stability. Thus a compromise between the three groups is necessary.

*i) **Minimising blast damage -*** Industry experience clearly shows that inappropriate blasting practices can result in substantial damage to the rock mass in the interim and final pit slopes. Examples of the outcome of poor blasting practices near open pit slopes include:

- Loose rock on slope faces and batter crests.
- Over-break in the slope face leading to over-steepening of the slope which in turn could lead to further instability depending on the level of stability allowed in the original design.
- Sub-grade damage which can destroy safety berms leading to a reduction in their effectiveness as a means of retention loose rock pieces falling from above.
- A cumulative reduction in the strength of rock mass in which the slope is developed. In particular, the shear strength of the structural defects will be reduced.

Consequently, the mine operator must develop and implement standardised drilling and blasting practices that have been based on well founded and recognised blast design procedures, and that are appropriate to the ground conditions at the mine site.

When developing standardised drilling and blasting practices, the mine operator must take into account all factors that control the level of slope damage caused by blasting; including:

- Geotechnical characteristics of the rock mass: dynamic compressive and tensile strength and elastic properties of rock material, structural defect properties such as orientation, persistence, spacing, roughness, aperture size, infilling material and shear strength.

Variations of these characteristics significantly influence the effectiveness of the blast as well as the extent of unnecessary damage to the slope.

- The presence of groundwater in the rock mass: water saturated rock masses transmit shock energy more efficiently than dry rock masses. The vibration and pressure levels do not attenuate quickly as in dry rock mass and the damage envelop is likely to be greater. Thus there is greater susceptibility to slope damage.

- Blast pattern parameters: amount of blast energy and rate of release. These depend on the type and mass of explosives, blast hole diameter, burden, spacing, sub-grade depth, blast hole orientation, stemming, initiation sequence and delay times.

- Static stability of the pit slopes: the level of static stability of the slope. The less stable a slope under static loading conditions, the more prone it will be to failure under dynamic loading during blasting.

Examples of measures commonly used to control blast-induced slope damage include: *Buffer blasting, *Trim blasting, *Pre-split or mid-split blasting, *Post-split blasting, *Line drilling, *Air decking, *Electronic delays.

It is essential, when designing site-specific controlled blasting techniques, to understand that each of these techniques has advantages and disadvantages depending on the site specific rock mass conditions and the slope design.

ii) ***Excavation control and Scaling-*** It must be acknowledged that adequate excavation and scaling of batter faces, (and selection of the mining equipment to be used to achieve the desired standards) are critical elements for the achievement and maintenance of safe slopes in all open pit mines. In soils and weak and weathered rock, batters can be excavated by free digging using hydraulic excavators. A critical factor in batter excavation in soils and weak rock is that the slope must not be under-cut such that the as-built slope is steeper than the as-designed. This could result in instability leading to safety implications. The berms separating the batters must be provided with adequate surface runoff control measures to minimise water infiltration and slope erosion. In these materials experienced machine operators can construct slopes with smooth surface so that scaling is not generally required.

In strong rocks, drilling and blasting is required to fragment the rock mass prior to the final preparation of the slope. Again care should be exercised to prevent over digging of the batter face, particularly where there is blast damage or fractured rock. Large equipment, primarily meant for loading blasted rock, should not be used for slopes construction because such equipment could cause excessive damage to the batter face. Scaling of the batter crest and face following the excavation is an important component of the implementation of the design. Scaling is intended to remove loose blocks and slabs that may form rockfalls or small failures. Scaling also helps preserve the catch capacity of berms – required to retain loose rock material drilling from above.

The debris accumulated at the toe of the batter after the scaling should be removed before the access to the toe is lost. This is necessary to maintain adequate catchment volume on the safety berm.

iii) ***Groundwater and surface water control -*** The open pit mines excavated below the ground water table need some form of dewatering and depressurisation. The most significant groundwater related problem is the effect that water pressure has on the stability of the pit slopes. Water pressures in structural defects in the rock mass and pore spaces in rock material reduce effective stress with a consequent reduction in shear strength.

At some mines with minor groundwater inflow from pit slopes and pit floor, evaporation alone can account for all dewatering requirements. At other mines major pumping operations are necessary. The approach to groundwater control can be by means of water abstraction methods such as:

- using in-pit and out-of-pit production bores,
- via sumps and/or trenches excavated into the pit floor, or
- through sub-horizontal drainage holes drilled into the pit slopes.

Each method can be used individually, or in combination to produce the required result. Selection of the most appropriate method will depend largely on the local and regional hydrogeological conditions, the relative importance of depressurisation to the mine design, and the required rate of mining. In major open pit mining operations all three methods may be required for groundwater control. The in-pit and out-of-pit production bores can be used in advance of and during mining.

Control of surface drainage is also an important aspect of the implementation of the slope design. Surface water drainage paths through and around the mine must be designed, constructed and maintained such that water does not pond at the crest or the toe of the critical slopes of the pit. Surface drainage design should take into account the consequences of flooding, including loss of life, injury to personnel, equipment damage, and loss of production. To reduce the potential risk of loss of life or injury to personnel, the surface drainage paths design should at least take into account 1 in 100 year 72 hour rainfall/flood event. The design criteria to be used will be dependent on the level of risk that the mine is willing to accept and can justify as meeting the regulatory requirements.

iv) ***Performance monitoring -*** Performance monitoring of open pit walls is required for essentially two purposes:

1. To verify the geotechnical parameters and assumptions used to design the existing walls.
2. To ensure that any potential falls of ground are detected prior to them becoming hazardous, and to establish appropriate trigger-action plans when ground movements are detected.

Validation of the geotechnical model is necessary due to; the inherent variability of geotechnical properties of naturally occurring geological materials; various uncertainties in the measurement of their engineering properties; the use of various (simplifying) assumptions during the geotechnical slope design process. Validation of the geotechnical model requires systematic monitoring of

ground conditions, drilling and blasting operations, excavation and scaling, dewatering measures, ground support and reinforcement installation and slope performance. Information used to validate the geotechnical model can be attained from sources such as:

- Geological and geotechnical mapping of exposed pit slopes, particularly batter faces
- Supplementary drilling, logging, testing and installation of instrumentation for the confirmation of geotechnical and hydrogeological characteristics of the deeper areas of the pit
- Performance monitoring of near wall blasting (i.e. the degree of shattering in batter face and back-break of batter crest) and ground movements
- Reconciliation of as-mined batter faces and berm widths
- Assessment of the effectiveness of dewatering and depressurisation measures, and
- Assessment of the effectiveness of mine planning and sequencing in achieving the designed slope configurations.

It should be noted that the detection of potential falls of ground, whilst obviously improving workplace safety, is a valuable tool for assessing the accuracy of initial slope design, and that pit slope movement data is essential for accurate assessment of failure risk, and the suitability of methods used to manage the safety risk.

Numerous techniques are available for pit slope monitoring include; various survey monitoring techniques; 3D-photogrammetry, wire and borehole extensometers; and radar monitoring systems. The selection of the most appropriate monitoring technique at a mine is dependent on site-specific conditions at the mine such as modes of failure, rock types, mining methods and mine planning strategies. Regardless of the technique used, if there is an adequate level of monitoring and a good understanding of the ground conditions, the onset of major pit slope failure can be detected in advance and the safety risks can be managed to an acceptable standard.

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Author's Published Books:

1. "*Acid mine drainage (AMD) and It's control*", Lambert Academic Publishing, Germany, (ISBN 978-3-8383-5522-1).

2. *"Mining and Blasting Techniques"*, LAP Lambert Academic Publishing, Germany, (ISBN 978-3-8383-7439-0).

3. *"Mining Operations"*, LAP Lambert Academic Publishing, Germany, (ISBN: 978-3-8383-8172-5).

4. *"Keeping World Environment Safer and Greener"*, LAP Lambert Academic Publishing, Germany. ISBN: 978-3-8383-8149-7.

5. *"Man And Environment"*, LAP Lambert Academic Publishing, Germany. ISBN: 978-3-8383-8338-5.

6. *"ENVIRONMENT AND POLLUTION"*, LAP Lambert Academic Publishing, Germany. ISBN: 978-3-8383-8651-5

Currently, author has following useful blogs on Web:

http://miningandblasting.wordpress.com/, http://saferenvironment.wordpress.com ,

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